Semiconductor Physics, Quantum Electronics & Optoelectronics, 2022. V. 25, No 3. P. 235-239.

Semiconductor physics

To 95-th birthday of Professor E.I. Rashba (looking back ones again)

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Abstract. The theory of spin-orbit interaction, developed by E.I. Rashba more than 30 years ago, stimulated the rapid development of a new discipline – spintronics – the physics of processes and devices based on the control of spins. The paper summarizes achievements of Prof. Rashba in the early stage of his scientific researches, particularly those, which were performed in Ukraine. Among them, prediction of electric dipole spin resonance (EDSR), phase transitions in spin-orbit coupled systems driven by change of the Fermi surface topology, giant oscillator strength of impurity excitons, and coexistence of free and self-trapped excitons.

Solid state physics is the basis of contemporary electronics and optoelectronics. Various electronic, optical, acoustical and other effects and processes in solid define performances of modern solid state devices. Multitude of groups and thousands researchers are involved in discovering, study and using relevant new phenomena. Among them, Professor Emmanuel Rashba with his outstanding results in physics of crystals is seen (rises) as a profound personality. His contribution in almost all branches of solid state physics cannot be exaggerated, some of his results have found important applications. Prof. E.I. Rashba is known as one of the leading theorists in Ukraine, in Soviet Union, and he continued the successful career in United States.

Although many years have already passed, scientific community in Ukraine remembers Prof. E.I. Rashba and thankfully appreciates his impact to formation of condensed matter researches in our country. This short text is devoted to Prof. E.I. Rashba and is written on the occasion of his birthday.

https://doi.org/10.15407/spqeo25.03.235
PACS 73.21.-b

Manuscript received 28.08.22; revised version received 20.09.22; accepted for publication 21.09.22; published online 06.10.22.

Emmanuil Iosifovich Rashba was born in Kyiv in 1927. In 1949 he graduated from the Department of Physics at the Kyiv State University, where he attended lectures by Profs S.I. Pekar, A.S. Davydov, N.N. Bogolyubov and K.B.Tolpygo. At the university, his scientific work was supervised by Profs S.I. Pekar and A.S. Davydov. After graduating from the university, he worked for several years as an engineer and teacher, and in his spare time he was engaged in theoretical studies of excitons. In 1954, E.I. Rashba was admitted to the Department of Semiconductors (guided by Academician V.E. Lashkaryov) at the Institute of Physics of the Academy of Sciences of the UkrSSR, where he worked closely with experimentalists and together with K.B. Tolpygo developed the theory of current carrier transport in semiconductors. One of the important results obtained at that time was the description of current-voltage characteristics inherent to rectifying diodes and *p-n* junctions in the limit of large biases (under the dissipative transport the currents are in proportion to the square of the applied voltage) [1, 2]. At the same time, E.I. Rashba continued his research on excitons [3, 4]. In 1956, being based on these results, he defended his PhD thesis under supervision of Prof. A.S. Davydov.

Further research on the theory of excitons was stimulated by new experimental results obtained in the Department of Spectroscopy at the Institute of Physics, Academy of Sciences of the UkrSSR (Department of Prof. A.F. Prikhotko). One such result is the discovery of spectral bands with anomalous absorption, which could not be directly attributed to excitons, however manifested a significant exciton-like polarization dependences. E.I. Rashba explained behavior of these spectra by constructing a theory of weakly coupled localized excitons. He found that the polarization and intensity of impurity bands show strong anomalies, when they are close to the actual exciton bands [5]. Later, already at the Institute of Semiconductors of the Academy of Sciences of the UkrSSR founded in 1960, a similar phenomenon was studied by E.I. Rashba for the Wannier–Mott excitons. In spectroscopy of crystals this effect – a giant increase in the oscillator strength – is called as the Rashba effect. In what follows, E.I. Rashba continued to keep interest in and study exciton phenomena at the Institute of Semiconductors.

In 1966, for his work on the theory of excitons in crystals, Professor E.I. Rashba has received the USSR State (Lenin) Prize together with a group of scientists, which included researchers from A.F. Ioffe Institute of Physics and Technology (E.F. Gross, B.P. Zakharchenya, A.A. Kaplyansky) and Institute of Physics of the Academy of Sciences of UkrSSR (A.S. Davydov, A.F. Prikhotko, V.L. Broude, A.F. Lubchenko and M.S. Brodin).

V.E. Lashkaryov's department at the Institute of Physics concentrated on studying the kinetics of photoconductivity in hexagonal A^2B^6 crystals of the CdS type, and E.I. Rashba focused on the features of optical spectra typical for these crystals. For this, it was necessary to study and apply the group theory. As a result, a complete analysis of the electron band structure of crystals without an inversion center was given including, particularly, the spin-orbit interaction [6, 7].

These results deserve particular consideration. Prior to the work of E.I. Rashba, no special attention was paid to spin-orbit interaction in crystals. There was the work by G. Dresselhaus [8], where the Hamiltonian of the spin-orbit interaction was introduced in the form proportional to the cube of the wave vector of the carrier. In the work of E.I. Rashba, the term describing this interaction linear in the wave vector was first introduced and substantiated. This result enabled to predict a new resonance arising under the action of an electric field and leading to a spin flip [9]. It should be noted that this work was approved by Academician L.D. Landau. The studies of spin-orbit interaction led to the prediction of combined resonance, in which the spin-orbit coupling, which leads to "entanglement" of motion in the real configuration and spin space, provides the possibility of a new type of transition excited by the electric vector of the high-frequency field and accompanied by a change in the effective spin momentum. In its intensity, the combined resonance can significantly exceed that of the paramagnetic resonance, and this resonance is especially strong in crystals without an inversion center; its frequencies are equal to linear combinations of the paramagnetic and cyclotron resonance ones.

Having begun at the Institute of Physics, Rashba's work on spin-orbit interaction was continued at the Institute of Semiconductors with involvement of young, at that time, V.I. Sheka and I.I. Boiko. The spin-orbit coupling also leads to the emergence of a special electron band structure, at which the energy extremum is reached on a circle – a loop of extrema, thus isoenergetic surfaces for small values of energy are toroids. The electronic properties of these semiconductors are very specific, in particular, a significant number of carriers can have the negative effective mass [10]. Other phenomena associated with the spin-orbit coupling in crystals without the inversion center have been also predicted and have become a standard method for measuring spin-orbit coupling.

The most complete review of experimental and theoretical results on the combined resonance and close effects was given by E.I. Rashba and V.I. Sheka in the monograph "Landau Level Spectroscopy", Ed. by G. Landwehr and E.I. Rashba (Elsevier, New York, 1991, p. 178). The pioneering work of E.I. Rashba on the combined resonance in semiconductor crystals was officially recognized as a discovery in the USSR.

For completeness of information, it is worth to note that working at the Institute of Semiconductors in 1963 E.I. Rashba defended the doctoral dissertation in the Academic Council at the A.F. Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR. The entire "Ukrainian period" of the E.I. Rashba scientific life is reflected in his article "Looking Back" published in the Journal of Superconductivity: Incorporating Novel Magnetism, v. 16, p. 599 (2003).

The following step in the theory of spin-orbit interaction was made at the Institute of Semiconductors at the time when semiconductor heterostructures appeared. Based on the studies carried out for bulk materials, F.T. Vasko proposed a Hamiltonian describing the spin-orbit interaction in quantum wells [11]. Later on, E.I. Rashba and Yu.A. Bychkov generalized this result in the paper [12]. Both these works created the basis for development of physics of spin-orbit interaction in the systems with low-dimensional current carriers. It is pertinent to note that different approaches to spin-orbit interaction and related effects have been discussed in the book [13] written by researchers from the Institute of Semiconductor Physics F.T. Vasko and O.E. Raichev.

More than 30 years later, the theory of the spin-orbit interaction, developed by E.I. Rashba, was used in the first work on the "spin transistor" [14], where it was proposed to control the spin precession by using the electrical field. With this work, the rapid development of a new discipline – spintronics – physics of processes and devices based on controlling the spins began. It became possible to expand the functionality of existing electronic devices by using the additional degree of freedom – the spin, to develop principles of new semiconductor nano-devices, particularly for quantum computations. Without any doubts, the works made by E.I. Rashba, including those carried out at the Institute of Physics and the Institute of Semiconductors of the National Academy of Sciences of Ukraine, are now among the most cited in the scientific literature on solids, semiconductors and semiconductor devices.

In the Institute of Semiconductors, the interests of E.I. Rashba were not limited by the above-mentioned exciton effects, electron band structure, and spin-orbit interaction. Anticipating the trends in the development of semiconductor devices and structures towards a significant reduction in spatial scales, E.I. Rashba proposed a series of ideas concerning new size effects that arise when device dimensions approach characteristic physical lengths. This is how the size effects associated with the recombination length in bipolar materials, with the intervalley relaxation length in multi-valley semiconductors, with the cooling length of carriers heated with an electric field, *etc*. The first works in this area carried out by the group of theorists and experimentalists at the Institute of Semiconductors appeared in 1965–1966 ([15]–[18]). Then, studies of the size effects proposed by E.I. Rashba became one of the main directions for the entire Institute of Semiconductors.

Here we would like to point out a few of these size effects, which bear the name of Rashba. The first one is the electric pinch effect in anisotropic bipolar materials – the field-controlled accumulation of electrons and holes near one of the semiconductor surfaces. Developing the ideas of Rashba, researchers from the Institute V.A. Romanov, I.P. Zhadko and V.K. Malyutenko created a whole set of new devices, including strain gauges, infrared detectors and emitters, *etc*.

Another important and unexpected phenomenon discovered by E.I. Rashba is related to manifestation of features of complex band structure in the electron transport. Specifically, for multi-valley crystals E.I. Rashba noted that distinct transport anisotropy of carriers belonging to different valleys facilitates their spatial separation [15] under the electric field in samples of restricted geometries (multi-valley Rashba size effect). In strong electric field this effect leads to formation of spatial domains populated dominantly by the electrons from one of the valleys [18]. A generalized analysis of theory and experiments in this area was given in the review [19]. Being proposed for such 'traditional' semiconductor materials as silicon, germanium, *etc*, the multi-valley Rashba size effect is exhibited in the modern quantum nanostructures (see the papers [20, 21] and references therein), which potentially presents promising applications for the emerging new discipline of nano-electronics – valleytronics (the use of the valley degree of freedom for information processing and storage applications, similar to spin in the mentioned above spintronics).

It should be noted that the interest of E.I. Rashba to manifestation of the features inherent to electron band structures in carrier transport involved many Ukrainian researchers to this subject. And still have a great impact for further theoretical and experimental studies. Indeed, the idea of electron motion with negative effective mass [11], later on received elaboration in the works by Z.S. Gribnikov with co-authors. They suggested to construct two-dimensional structures, for which the energy dispersion of carriers holds a portion of negative effective mass and showed that these structures are capable to generate THz emission (see [22–24] and references therein). Rashba's attention to multi-valley semiconductors has induced development of equilibrium phase transitions in these crystals, which results in anisotropic lattice deformation accompanied by formation of an energy gap between equivalent valleys and by the redistribution of carriers between displaced valleys [25], and non-equilibrium phase transitions in the strong electric field – multi-valued Sasaki effect [26, 27].

In 1967, Emmanuil Iosifovich Rashba moved to the L.D. Landau Institute of Theoretical Physics, where he headed the Department of Semiconductor Theory. He continued an active research career, combining it with the work in the most prestigious physical journals in the USSR, where he worked from 1973 up to 1988. He maintained and still maintains active ties with the Institute of Semiconductor Physics of National Academy of Sciences of Ukraine (former the Institute of Semiconductors) as evidenced by the cited reviews and a large number of joint scientific publications. E.I. Rashba's contribution to the development of science in Ukraine, in particular, was appreciated by awarding him in 2007 the S.I. Pekar Prize of the National Academy of Sciences of Ukraine for outstanding achievements in the field of solid state theory. In 1987, he received the prestigious A.F. Ioffe Prize of the USSR Academy of Sciences. In 1991, E.I. Rashba moved to the USA, where he continues to actively work as a professor at Harvard University, also being a honorary professor at a number of other prestigious US universities. His scientific authority is enormous, he has been awarded a number of international scientific awards, international conferences are held in his honor. And among them: Alan Berman Res. Publ. Award of Naval Res. Lab (USA) – 2001; Symposium in Honor of E.I. Rashba (Boston) – 2002; NATO Adv. Res. Workshop on Frontiers of Spintronics & Optics; The Sir Nevill Mott Lecture (United Kingdom) – 2005; Symposium in Honor of E.I. Rashba, Frontiers of Spintronics, Cambridge (USA) – 2008); Special issue of the "International Journal on Superconductivity and Magnetism" Frontiers of Spintronics and Optics in Semiconductors: In Honor of E.I. Rashba, v. 16, No. 4, (2003); Oliver E. Buckley Prize on Condensed Matter Physics (2022).

Thus, solid state physics is the basis of contemporary electronics and optoelectronics. Professor Emmanuil Rashba with his outstanding results on physics of crystals plays a profound personality. His contributions in almost all branches of the solid state physics are significant, some of his results have found important applications. The paper summarizes achievements of Prof. Rashba in early stage of his scientific research.

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До 95-річчя від дня народження професора Е. І. Рашби (знову оглядаючись назад)

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Анотація. Теорія спін-орбітальної взаємодії, розроблена Е.І. Рашбою більше 30 років тому, стимулювала бурхливий розвиток нової дисципліни – спінтроніки – фізики процесів і пристроїв, основаних на управлінні спінами. У статті узагальнено досягнення професора Рашби на ранньому етапі його наукових досліджень, зокрема тих, що проводилися в Україні. Серед них – передбачення електричного дипольного спінового резонансу (EDSR), фазових переходів у спін-орбітальних зв'язаних системах, викликаних зміною топології поверхні Фермі, сили гігантського осцилятора домішкових екситонів і співіснування вільних і самозахоплених екситонів.

Фізика твердого тіла є основою сучасної електроніки та оптоелектроніки. Різні електронні, оптичні, акустичні та інші ефекти і процеси у твердому тілі визначають характеристики сучасних твердотільних пристроїв. Багато груп і тисячі дослідників залучені до відкриття, вивчення та використання відповідних нових явищ. Серед них професор Еммануїл Рашба з його видатними результатами у фізиці кристалів розглядається (підноситься) як глибока особистість. Його внесок у майже всі галузі фізики твердого тіла неможливо перебільшити, деякі з його результатів знайшли важливе застосування. Проф. Є.І. Рашба відомий як один із провідних теоретиків в Україні, в Радянському Союзі, потім він продовжив успішну кар'єру в США.

Хоча минуло вже багато років, наукова громадськість України пам'ятає професора Є.І. Рашбу і з вдячністю оцінює його вплив на становлення досліджень конденсованого стану в нашій країні. Цей короткий текст присвячено професору Є.І. Рашба і написано з нагоди його дня народження.